Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **25**, 115–133 (2000)

QUANTITATIVE MODEL OF THE GROWTH OF FLOODPLAINS BY VERTICAL ACCRETION

JOHN A. MOODY* AND BRENT M. TROUTMAN
US Geological Survey, Water Resources Division, Mail Stop 413, Denver Federal Center, Lakewood, Colorado 80225, USA

Received 25 February 1998; Revised 25 March 1999; Accepted 21 May 1999

ABSTRACT

A simple one-dimensional model is developed to quantitatively predict the change in elevation, over a period of decades, for vertically accreting floodplains. This unsteady model approximates the monotonic growth of a floodplain as an incremental but constant increase of net sediment deposition per flood for those floods of a partial duration series that exceed a threshold discharge corresponding to the elevation of the floodplain. Sediment deposition from each flood increases the elevation of the floodplain and consequently the magnitude of the threshold discharge resulting in a decrease in the number of floods and growth rate of the floodplain.

Floodplain growth curves predicted by this model are compared to empirical growth curves based on dendrochronology and to direct field measurements at five floodplain sites. The model was used to predict the value of net sediment deposition per flood which best fits (in a least squares sense) the empirical and field measurements; these values fall within the range of independent estimates of the net sediment deposition per flood based on empirical equations. These empirical equations permit the application of the model to estimate of floodplain growth for other floodplains throughout the world which do not have detailed data of sediment deposition during individual floods. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: floodplain growth; fluvial geomorphology; vertical accretion

INTRODUCTION

North American floodplains have gone through a rapid cycle of utility within the short time span of European occupation. Initially, floodplains were important as locations near water for settlements and agriculture. Later, some floodplains were abandoned or used for dumping waste products. More recently, they have regained respect and are now recognized as important features of the fluvial ecosystem. Interest in the restoration of rivers (US Department of Agriculture, 1979; Petts *et al.*, 1992; National Research Council, 1992; Bayley, 1995; Swanson, 1997), the origin of ecotones (Salo, 1990), the storage and remobilization of contaminants such as mining wastes (Gilbert, 1917; Kennedy, 1956; Lewin *et al.*, 1977; Marron, 1992), radioactive wastes (Miller and Wells, 1986; Graf, 1994), urban wastes (Leenaers and Schouten, 1989) and chemicals (Sciacca, 1998), the possibility that rivers and their floodplains might be sinks for the 'missing' carbon in the carbon cycle (Stallard, 1998), and the interaction between channel and floodplain processes (Sellin, 1964; Wolff and Burges, 1994; Brierley *et al.*, 1997; Cazanacli and Smith, 1997) can be advanced with the development of models of floodplain growth on a secular time scale of decades.

Models of floodplain growth have been developed at several time and spatial scales. The avulsion model (Bridge and Leeder, 1979; Bridge and Mackey, 1993) has been developed for time scales of several thousand years in order to interpret ancient alluvium such as coarse-grained sandstone bodies which may serve as reservoirs for hydrocarbon. For shorter time scales, Howard (1992) has developed a meandering-sedimentation model that couples bank erosion and meandering with primarily diffusive floodplain sedimentation. Both models simplify the floodplain building processes by assuming that mean deposition

* Correspondence to: J. A. Moody, US Geological Survey, Water Resources Division, Mail Stop 413, Denver Federal Center, Lakewood, Colorado 80225, USA.

CCC 0197-9337/2000/020115–19 $17.50

rates are steady for long time intervals and that the same processes act over large spatial scales of 10^5–10^6 m encompassing entire basins. These assumptions are not used in the spatially dependent floodplain model of Nicholas and Walling (1997a, 1997b), which focuses on predicting the detailed, two-dimensional distribution of sedimentation thickness over relatively small spatial scales of 10–10^3 m during individual floods at time scales of only 3–5 days. Nor are these assumptions used in the steady, longitudinal flow model of James (1985) which has been verified in the laboratory for even smaller spatial scales of 0·1–1 m. None of these floodplain growth models addresses the unsteady flow problem or the vertical aggradation of floodplains during individual floods over the secular time scale.

River basins are so widely variable in their width, slope and alluvial material that any single type of floodplain building process is unlikely to prevail throughout a basin. Nanson and Young (1981) have discussed the two views of the floodplain building process: point bar-lateral migration (Wolman and Leopold, 1957; Leopold *et al.*, 1964) and overbank vertical accretion (Melton, 1936; Blake and Ollier, 1971; Ritter *et al.*, 1973; Stene, 1980; Nanson, 1986). Nanson and Croke (1992) later classified the floodplain spectrum into three classes (each class contains subclasses or orders) based on stream power and boundary resistance; these range from high-energy non-cohesive floodplains (Class A) typically located in steep headwaters, to medium-energy non-cohesive floodplains (Class B), to low-energy cohesive floodplains (Class C) with low gradients. Stream power character varies from extreme, short-lasting (flash) floods with episodic frequencies to a mixture of floods occurring several times a year to long-lasting floods with only annual frequency. These individual floods create floodplain stratigraphy which by its nature indicates that the sedimentation is not continuous (Brakenridge, 1988), being an accumulation of layers from discrete floods, each with a different character.

Many different classes of floodplains coexist within any river basin and since it is improbable that any single model of floodplain growth could simulate all of the possible variations then models will, for the near future, represent only certain floodplain classes or processes within a class. One process, point-bar lateral migration, has been described by both qualitative facies models (Jackson, 1976) and quantitative models (Allen, 1970, 1977; Bridge, 1975). These models are specifically applicable to building floodplains within the channel of a meandering river up to the elevation of the surrounding floodplain (Class B3; Nanson and Croke, 1992) for short temporal and spatial scales. Another process, overbank vertical accretion, has been described qualitatively by Blake and Ollier (1971), Nanson (1986) and Moody *et al.* (1999) but only a quantitative diffusion model (Pizzuto, 1987) has been developed and some doubt exists whether or not diffusion is the correct process to use in modelling overbank, vertically accreting floodplains.

Examples of the overbank vertical-accretion process are the channel-expansion floodplains described by Moody *et al.* (1999) which have developed within a channel widened by a catastrophic flood (similar to Class A3; Nanson and Croke, 1992) on the Powder River in southeast Montana. Following the catastrophic flood of 1978, new floodplains grew within the widened channel by overbank suspended-sediment deposition from a mixed population of moderate floods. These moderate floods were caused by ice jams following the snowmelt at low elevations in the late winter–early spring, by snowmelt at high elevations in late spring–early summer, and by flash floods following localized summer thunderstorms. Similar channel-expansion type floodplains have developed along the Cimarron River in southwestern Kansas (Schumm and Lichty, 1963), and along Plum Creek in Colorado (Friedman *et al.*, 1996). Along the Green River in Utah, reductions in flood discharges (as a result of the closing of the Flaming Gorge Dam in 1962) have produced the same effect as channel widening (Allred, pers. comm., 1999). Along some reaches of the river, the channel expands significantly during high discharges but is laterally stable, and overbank vertical accretion is the dominant process. Along other reaches, point-bar lateral migration is the dominant process, and floodplain building processes are mixed.

This paper describes a quantitative floodplain growth model based on the unsteady nature of the vertically accreting channel-expansion floodplains along the Powder River. Powder River is one of the few relatively large (annual mean discharge is 12·8 m^3 s^{-1}) unregulated rivers in the United States with plenty of suspended sediment (annual mean concentration is 6200 mg l^{-1}). As such, it provides an outdoor laboratory to study, in accelerated time, how other floodplains with perhaps less suspended sediment might develop. In contrast to other models (Bridge and Leeder, 1979; James, 1985; Pizzuto, 1987; Bridge and Mackey, 1993; Nicholas and

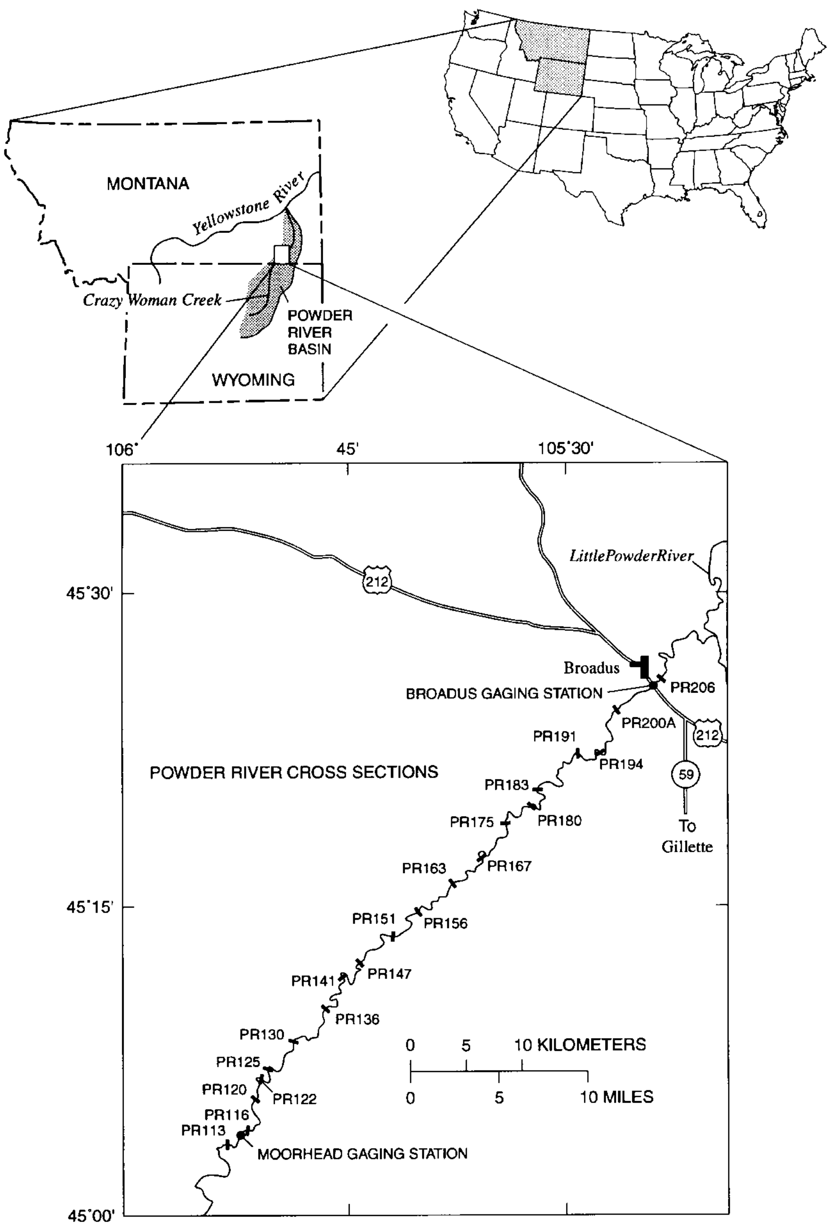

Figure 1. Location of the cross-sections on Powder River. Cross-sections PR120, PR125, PR136, PR151 and PR156A are the five channel-expansion vertically accreting floodplains used to develop the incremental-growth model

Walling, 1997a, 1997b) that assume a steady-state continuous process, the incremental-growth model described in this paper is formulated to represent floodplain growth as the accumulation of equal sediment layers deposited by discrete but random floods several times per year over a secular time scale. The model focuses on the growth of the floodplain crest or levee which is the important interface where mass and momentum are exchanged (Knight and Hamed, 1984; Rouvé and Stein, 1990; Brierley *et al.*, 1997). The general applicability of the incremental-growth model is tested first with data from two other rivers having similar climatic conditions, Little Missouri River in western North Dakota (Everitt, 1968) and Beatton River in northeastern British Columbia (Hickin and Nanson, 1975; Nanson and Beach, 1977), and one having different climatic conditions, Brandywine Creek in southeastern Pennsylvania (Wolman, 1955; Wolman and

Leopold, 1957; Pizzuto, 1987). The paper concludes with a discussion of applications to other floodplains in the world.

MODEL DEVELOPMENT

This incremental-growth model for floodplains is a quantitative model which predicts the elevation of the floodplain with time and is similar to the one suggested and used by Wolman and Leopold for Brandywine Creek in southeastern Pennsylvania (Wolman, 1955; Wolman and Leopold, 1957): 'If a specific thickness of material were deposited on the flood plain every time a river over flowed its banks it would be possible to compute the rate of rise of the flood-plain surface by the use of flood frequency data.' This model has been developed for vertically accreting floodplains along Powder River (Figure 1) which has certain hydraulic and sedimentologic characteristics and for which 18 years of net sediment deposition data exist. It is a one-dimensional model, using a partial-duration flood series to predict the vertical growth of the floodplain crest or levee as a consequence of net sediment deposition by all floods which are higher than the floodplain crest or levee. Data for sediment deposition per flood for the Powder River are used to calibrate an empirical equation for predicting flood deposition along other rivers.

Hydraulic and sedimentologic characteristics

The model is based on 18 years of data for five of 23 cross-sections on the Powder River which are examples of vertically accreting channel-expansion floodplains. The change in elevation of the channel bed in the Powder River has not shown any consistent trend since the 1978 flood. Linear regressions of the minimum riverbed elevation versus time after the 1978 flood (for the five sections PR120, PR125, PR136, PR151 and PR156A; Figure 2) indicated increasing (two sections), decreasing (two sections), and no change (one section) in the elevation of the channel bed with time. Correlation coefficients were less than 0·68 for all five sections and averaged 0·28. Other cross-sections (18) representing other types of floodplains did not show any consistent trend in changes of the channel bed elevation between 1978 and 1998. Other investigators have reported similar observations for the Gila River (Burkham, 1972), Brandywine Creek (Pizzuto, 1987) and Paria River (Topping, 1997). Thus, the incremental-growth model assumes that the minimum bed elevation is constant. This is not a fixed restraint, however, and the possibility of the channel bed changing relative to the floodplain is investigated later.

The bedload component (83 per cent bed material is >0·125 mm) in the Powder River is only 2–7 per cent of the suspended load (Hembree *et al.*, 1952; Litke, 1983; Moody and Meade, 1990) and the floodplains are composed primarily of very fine sand (0·063–0·125 mm) and silt (82 per cent finer than 0·125 mm; Moody *et al.* 1999). During high discharge, some of the bed material that moves as bedload at low discharge becomes part of the suspended load and thus the bedload is an even smaller proportion of the suspended load during floods. Therefore, the bedload component is neglected (as a first order approximation) in the incremental-growth model and the initial process of sedimentation on the floodplains is assumed to be suspended-sediment deposition.

The effect of the floodplain on the stage–discharge relation is also negligible depending upon the ratios of the floodplain width to channel width, floodplain flow depth to channel flow depth, and floodplain roughness to channel roughness. To estimate this effect we can imagine a barrier at the edge of a rectangular channel of width W, which prevents water from entering a level floodplain of width w, so that the stage–discharge relation is:

$$Q = \frac{Wh^{5/3}S^{1/2}}{n_c} \tag{1}$$

where a Manning-type resistance, n_c, is assumed in the channel, h is the water depth in the channel, and S is the water-surface slope. If the water depth is above the floodplain and the barrier is removed allowing water to flow at a depth d, downstream across the floodplain with a roughness of n_f, then an estimate of the change

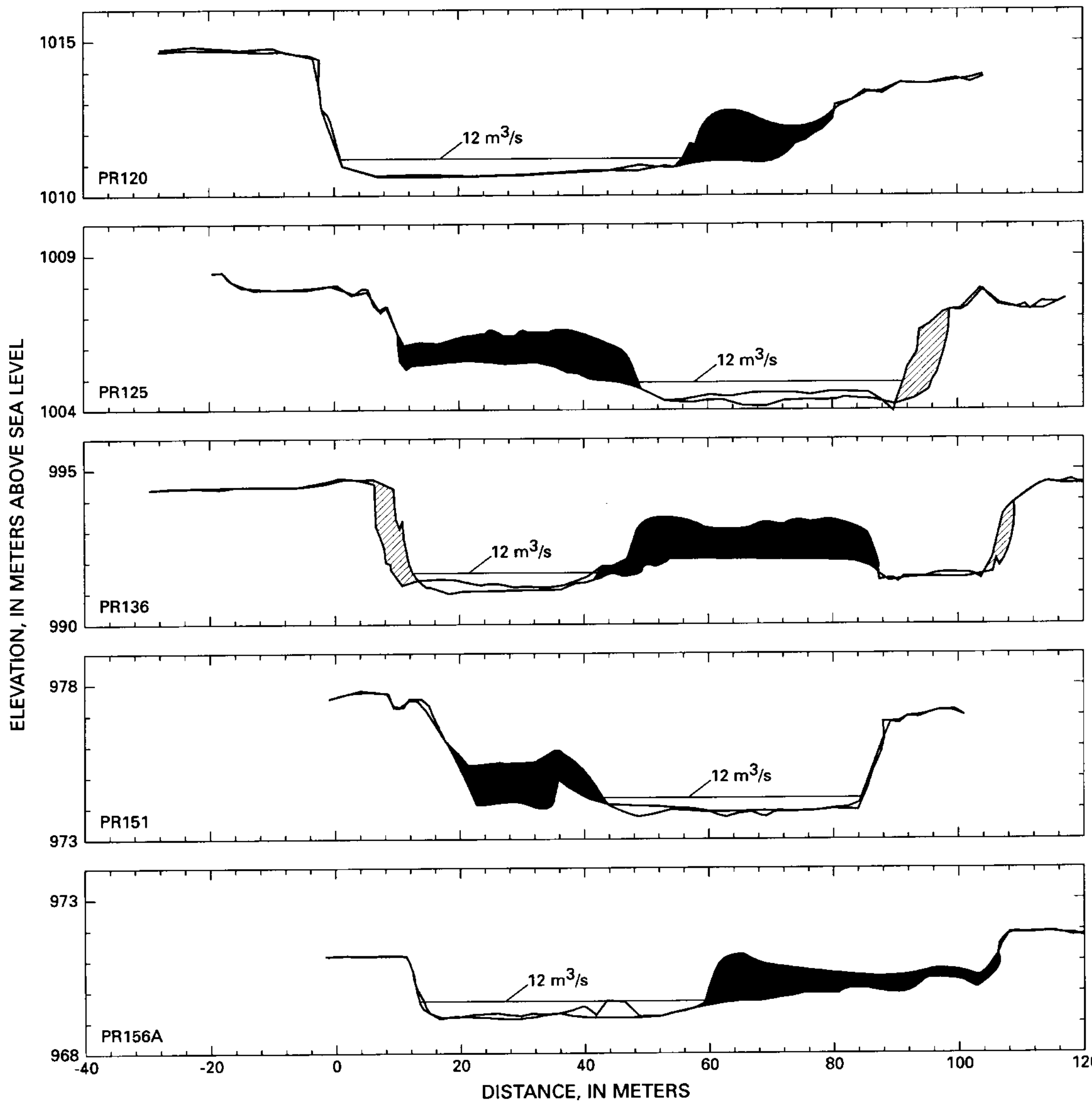

Figure 2. Five examples of channel-expansion floodplains that have evolved by mostly vertical accretion in the flood-widened channel of Powder River. The 1978 and 1996 surfaces are shown as solid lines. The cross-hatched areas represent net erosion and the solid black areas represent net deposition. The bedfull discharge ($12{\cdot}8\ m^3\ s^{-1}$) is the discharge required to fill the channel to the break in slope between the bank and channel and corresponds to the lower limit of vegetation. The elevation of the bedfull discharge is shown as a horizontal line. The bankfull or threshold discharge is defined as the water discharge that corresponds to the highest elevation of the floodplain

in depth or stage, Δh, relative to the channel depth, h, will be:

$$\frac{\Delta h}{h} = \left\{ \left[\left(\frac{w}{W}\right)\left(\frac{n_c}{n_f}\right)\left(\frac{d}{h}\right)^{5/3} + 1 \right]^{3/5} - 1 \right\} \tag{2}$$

assuming the longitudinal surface slope is the same over the channel and the floodplain. For Powder River, the values of w/W for the five sections ranged from 0·33 to 0·96, n_c is approximately 0·04 (Barnes, 1967), and $n_f = 0{\cdot}12$ is estimated from measurements made on grass-covered floodplains (Chow, 1959; Collins and

Table I. Flood frequency characteristics of four floodplains

River	Minimum discharge ($m^3 s^{-1}$)	λ	Discharge ($m^3 s^{-1}$)		Ln (discharge)		Duration (days)		Ln (duration)	
			Max.	Med.	Mean	SD	Max.	Med.	Mean	SD
Beatton River near Fort St. John, British Columbia	52·5	3·2	1700	277	5·51	0·99	105	17	2·76	1·13
Brandywine Creek at Chadds Ford, Penn.	11·2	17·8	300	20·7	3·21	0·68	209	2	0·94	1·04
Little Missouri R. near Watford, North Dakota	15·4	6·1	1560	39·4	3·97	1·06	95	5	1·63	1·23
Powder River at Moorhead, Montana	12·8	6·4	779	25·3	3·52	0·88	129	5	1·75	1·25

Based on daily mean discharges greater than the minimum discharge equal to the annual mean discharge; λ is the mean number of floods per year greater than the annual mean discharge; Max., maximum; Med., median, SD, standard deviation

Flynn, 1978). The family of curves defined by w/W for $\Delta h/h$ versus d/h indicates that for shallow flow depths on the floodplain ($d/h < 0{\cdot}2$) the change in stage is <2 per cent and is <5 per cent for $d/h < 0{\cdot}4$. Thus, the stage–discharge relation will not change significantly for stages slightly above the elevation of the floodplain; this was also shown by Knight and Demetriou (1983) for smooth floodplains in a flume. As the floodplain grows vertically upward, the imaginary barrier becomes the real levee maintaining the stage–discharge relation. This small effect is also supported by unpublished data from the Green River near Green River (Allred, pers. comm., 1999) where an analogous channel-expansion floodplain developed at the gauging cross-section and the stage–discharge relation did not change significantly based on the fact that the minimum riverbed elevation did not indicate any trend with time. Therefore, the observed decrease of sedimentation with time on floodplains noted by several authors (Wolman and Leopold, 1957; Everitt, 1968; Nanson, 1980; Howard, 1992) is modelled by the incremental-growth model as a consequence of the increase in elevation of the floodplain which increases the threshold or bankfull discharge because the stage–discharge relation and channel bed elevation remain fixed. Thus, as flood discharges increase, the frequency of flooding decreases and the net sediment deposition decreases with time.

Partial duration flood series

Floodplain growth does not occur only during the maximum annual flood but, as Wolman and Miller (1960) point out, during moderate but more frequent floods. These floods are sufficiently large to cover the floodplain and recur ‘at least once each year or two and in many cases several or more times per year’ (Wolman and Miller, 1960) and in some cases as much as seven times per year (Lambert and Walling, 1987). For this reason, we use the partial-duration series rather than the annual maximum series to determine the flood frequency characteristics (Table I). Unlike the annual series, the partial-duration series is defined by floods which exceed a baseflow discharge (Chow, 1964). In this paper, we have selected the base value to be the bedfull discharge because it is an important hydrogeomorphic parameter (Brakenridge, 1988) and corresponds to the reference level used by Osterkamp and Hedman (1982) and the normal stage defined by Brakenridge (1988). It is defined geomorphically to be the discharge when the water level is at the elevation of the break in slope between the relatively steep bank and the nearly level mobile channel bed. This usually coincides with the lower limit of vegetation (Hupp and Osterkamp, 1985) which is indicative of a floodplain and is perhaps easier to identify than bankfull discharge. Discharges less than bedfull flow are not relevant to

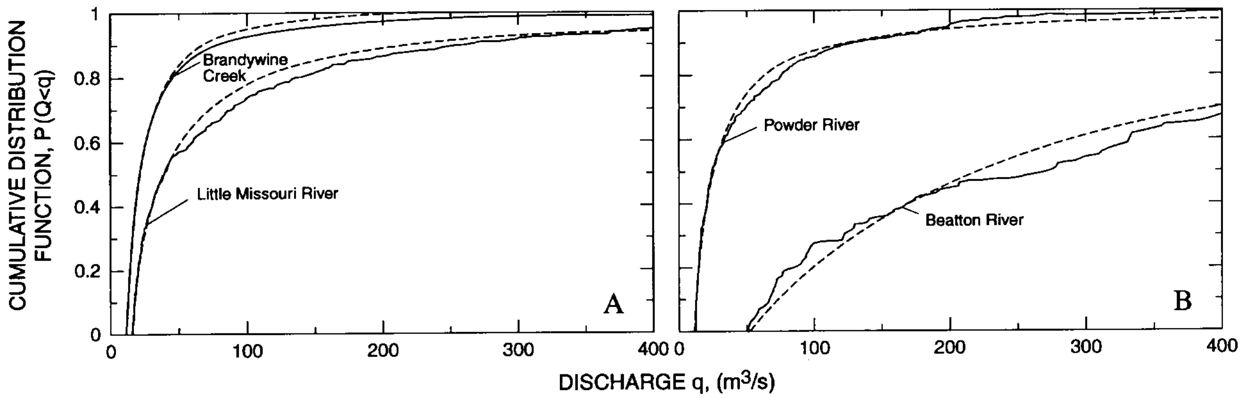

Figure 3. Theoretical truncated log-normal (dashed line) and empirical (solid line) cumulative probability distributions for: (A) Brandywine Creek and Little Missouri River, and (B) Powder and Beatton Rivers

floodplain growth. For Powder River the bedfull discharge is $12{\cdot}8\ m^3\ s^{-1}$. It actually equals the baseflow defined as the time average or annual mean discharge, and is exceeded only 24 per cent of the time. Between 1 October 1929 and 30 September 1995 (excluding 1973 when no data were collected), 429 floods in Powder River were greater than $12{\cdot}8\ m^3\ s^{-1}$ corresponding to an average of 6·4 floods per year with a median duration of 5 days. Similar data for the Beatton River, Brandywine Creek and Little Missouri River are listed in Table I, and because the bedfull discharge was not known for these rivers, the time-averaged annual mean discharge or baseflow discharge is listed.

Flood frequency distributions have been approximated as log-normal distributions (Chow, 1954; Wolman and Miller, 1960) and because the partial-duration flood series is defined by a baseflow discharge we have used a truncated log-normal probability distribution given by:

$$F(q) = \int_{Q_M}^{q} \frac{\kappa}{x\sigma\sqrt{2\pi}} e^{\frac{-(\log x-\zeta)^2}{2\sigma^2}} dx, q \geq Q_M \tag{3}$$

where Q_M is a baseflow discharge chosen to be either the baseflow or annual mean discharge, ζ and σ^2 are the mean and variance of the log-transformed discharges, and κ is a normalizing constant. Estimates of the parameters were obtained by the method of maximum likelihood (Johnson and Kotz, 1970, section 7·1). The goodness-of-fit to the truncated log-normal distribution was then tested using a chi-square test. The chi-square goodness-of-fit test requires that the data be put in arbitrary groups (Conover, 1980) so that 10 equal intervals of ln q were selected (ranging from the minimum discharge to the maximum discharge) to provide a minimal sampling of the distribution. Value of χ^2 for the goodness-of-fit test was 0·065 for the Powder River and ranged from 0·012 to 0·14 for the other three rivers (all were much less than the critical χ^2 value of 2·17 for the 5 per cent level of significance with seven degrees of freedom). These truncated log-normal cumulative probability distributions are shown in Figure 3 along with the empirical cumulative probability distribution. Brandywine Creek, Little Missouri River and Powder River have similar median discharges which are about one-tenth the median discharge for the Beatton River (Table I).

Floods on many rivers in the temperate zone represent a mixed population derived from several sources which vary in importance depending upon the size of the river. Floods on Powder River are from one of three populations: ice jams, snowmelt and thunderstorms. Each population is directly or indirectly related to precipitation events but each is definitely independent of the others in time. Exponential distributions have been used to describe random arrival times of such independent hydrologic events (Brooks and Carruthers, 1953; Duckstein *et al.*, 1972; Chow *et al.*, 1988). The number of events as a function of time is described by a

Poisson process where event inter-arrival times are exponential and independent. The parameter λ for the process is the mean number of floods per year (Table I) and is estimated by N/n, where N is the total number of floods occurring in n years. Brandywine Creek has about three times more floods per year than either the Little Missouri or the Powder River. The Beatton River has the fewest floods per year and these occur from April to October (43 per cent in May and June) whereas the Little Missouri and Powder Rivers have some floods in February, March and November (27–30 per cent in May and June), and Brandywine Creek has a fairly even distribution of floods throughout the year (18 per cent in May and June). In general during floods, six phases of sediment erosion and deposition have been described (Zwolinski, 1992); however, at the present time, the physics of erosion and deposition during a flood are poorly quantified so that the actual amounts of erosion and deposition cannot be calculated and therefore the net sediment deposition (deposition minus erosion) must be estimated.

Net sediment deposition rate

Sediment deposition rates are easier to quantify than erosion rates because simple settling is much easier to model mathematically than the complex hydraulic processes involved in erosion. In general, most mathematical models have used depth-integrated mass balance equations to specify the deposition or erosion (source or sink) terms in a one- or two-dimensional model. A steady-state model of Pizzuto (1987) avoided specifying both deposition and erosion rates by using 'an equilibrium vertically integrated concentration' which allowed him to predict relative deposition rates and he estimated the deposition rate per flood by dividing the total accumulation by the number of floods giving an average deposition per flood of 1·4 cm for Brandywine Creek. The two-dimensional, step-wise, steady-state model of Nicholas and Walling (1997a) specified a net sediment deposition rate but reported difficulty in using Engelund (1970) and Parker (1978) equations when flow depths on floodplains approached zero and therefore they used an empirical relation requiring calibration. Total net deposition for a single flood lasting 5 days was then calculated as the sum of the deposition at each time step at each grid node and ranged from 0 to 0·10 cm (assuming a bulk density of 1·2 g cm^{-3}). This suggests that using an empirical approach based on field measurements will simplify the complex unsteady problem (involving the variation of sediment concentration, particle-size distribution, turbulent eddy diffusivities, vertical velocity profiles as functions of time as well as spatially variable floodplain topography) until a useful physically based solution can be found for predicting the deposition per flood in shallow-water conditions.

Field measurements of sediment deposition during a single flood vary depending upon the river and the location relative to the river, and are usually measurements for catastrophic floods. Such catastrophic floods have deposited 122–183 cm on Missouri River levees in 1881, 0·5–84 cm on the Mississippi River (excluding point bars) in 1973, 0·2–60 cm on the Ob' River (excluding point bars) in 1969, and 0·3–56 cm on the Ohio River in 1937 (Bridge and Leeder, 1979); however, most of the 'work' is done by more frequent, moderate floods (Wolman and Miller, 1960). Average cross-sectional net deposition rates for 50 such moderate floods at the five cross-sections during 18 years on Powder River ranged from −3·5 to 9·0 cm/flood with a mean of 1·5 cm/flood (Table 2). Net deposition on the levee was greater and ranged from −5·5 to 26·0 cm/flood with a mean of 2·4 cm/flood. As a first approximation, the net deposition per flood is considered as a constant; however, the annual deposition will vary depending upon the number of floods each year.

Data on net sediment deposition per flood may not exist for other rivers, so that an estimate can be made by combining the field data from the Powder River with an empirical equation. Howard (1992) proposed in his channel migration model of a floodplain that the deposition rate depends upon the relative floodplain height but this seems to require knowing the unknown–the 'maximum floodplain height'. Others (Parker, 1978; Pizzuto, 1987) have suggested an equation for the deposition rate, D_r, as a function of sediment diffusivity which depends on actual flow conditions, but this is not conducive to *a priori* estimates of the deposition rate and, as mentioned above, Nicholas and Walling (1997a) found it difficult to use this type of equation in shallow water so they proposed the empirical equation:

$$D_r = kV_s\bar{C} \tag{4}$$

Table II. Net sediment deposition per flood at five cross-sections on Powder River

	PR120			PR125			PR136			PR151			PR156A		
Water year	N_F	$\overline{D}$	D_L	N_F	$\overline{D}$	D_L	N_F	$\overline{D}$	D_L	N_F	$\overline{D}$	D_L	N_F	$\overline{D}$	D_L
1979	3	1·7	nc	2	0·9	0·0	1	−2·8	−2·0	0	–	–	1	2·0	nc
1980	6	0·3	nc	2	1·6	1·0	2	0·05	−1·5	4	1·2	2·2	2	−0·2	−5·5
1981–82	8	2·2	5·2	7	3·2	2·9	6	4·4	6·2	6	0·6	4·0	7	1·6	5·0
1983–84	4	0·8	4·0	4	1·6	1·0	4	0·5	0·8	2	8·0	6·0	3	1·5	4·7
1985	0	–	–	0	–	–	0	–	–	0	–	–	0	–	–
1986	2	0·9	3·0	4	0·9	−0·5	4	1·3	1·0	4	0·7	3·2	2	1·2	0·5
1987	4	3·0	5·0	4	2·0	5·5	4	3·3	4·8	4	0·9	2·2	4	2·1	4·5
1988	0	–	–	0	–	–	0	–	–	0	–	–	0	–	–
1989	1	1·7	0·0	1	0·3	−1·0	1	−3·5	2·0	1	−0·1	−2·0	1	1·5	−2·0
1990	2	4·4	6·0	2	3·2	2·5	2	1·8	−0·5	2	1·7	0·5	2	1·2	3·0
1991	4	−0·4	−1·5	4	0·8	−0·2	4	0·25	0·5	4	−0·1	0·2	4	0·2	−0·5
1992	3	0·5	−1·7	3	0·4	0·3	2	0·05	1·0	3	0·6	−0·3	3	−0·07	−0·7
1993	7	1·2	3·6	7	1·7	1·7	7	2·1	0·7	7	0·5	2·7	7	1·3	1·6
1994	1	2·2	0·0	1	2·5	2·0	1	4·4	1·0	1	0·2	3·0	1	1·0	26·0
1995	3	3·2	7·0	3	5·3	6·3	3	9·0	15·3	3	2·5	11·7	3	4·2	6·7
1996	2	0·4	0·0	2	0·3	−0·5	1	1·6	2·0	2	0·0	−0·5	2	−0·3	−2·5

	$\overline{D}$	D_L
Minimum	−3·5	−5·5
25 percentile	0·3	−0·2
Median	1·2	1·6
Mean	1·5	2·4
75 percentile	2·3	4·0
Maximum	9·0	26·0

($\overline{D}$ in cm/flood) is floodplain cross-sectional average net deposition (deposition−erosion) divided by number of floods, N_F; D_L (in cm/flood) is the net deposition on the levee divided by number of floods, N_F; nc = no levee crest. Note that floods at one cross-section are not always floods at other cross-sections

where V_s is the settling velocity of the sediment, $\overline{C}$ is the depth-averaged suspended-sediment concentration, and k is an empirical constant. The deposition per flood, D_f, can then be approximated as:

$$D_f = \frac{kV_s\bar{C}\Delta T}{\rho_s} \tag{5}$$

where ΔT is the duration of the flood and ρ_s is the bulk sediment density. A range of values for k can be defined by using the empirical equation and the Powder River data (Table II) for cross-section average net sediment deposition per flood, $\overline{D}$, or the net sediment deposition per flood on the levee, D_L. D_f was set equal to the minimum, mean and maximum values of $\overline{D}$ and D_L; V_s (1·0 cm s^{-1}) was chosen for very fine sand; the concentration, $\overline{D}$, was equal to the concentration of the median flood; and ΔT was equal to the median duration (Table I). The concentration of the median flood was calculated using an empirical equation for Powder River at Moorhead, Montana:

$$\bar{C} = 220Q \tag{6}$$

similar to empirical equations given by Litke (1983) for the Powder River at Moorhead ($\overline{C} = 70Q^{1·22}$) and at Broadus ($\overline{C} = 410Q^{0·73}$), Montana (located about 90 km downstream from Moorhead). The net deposition per flood, $\overline{D}$ and D_L, for the other three rivers (Table III) varies by about two orders of magnitude which provides a good test of the incremental-growth model to predict floodplain growth curves.

Incremental-growth model

The incremental-growth model represents the increase in the average elevation across the floodplain not as a continuous process in time but as an incremental process that raises the elevation of the floodplain during each flood by a constant thickness equal to the net deposition per flood, D_f. Furthermore, since the minimum bed elevation is constant and the effect of the floodplain is negligible on the stage–discharge relation then the mean depth, h, and the discharge, Q, are related by:

$$h = cQ^f \tag{7}$$

The initial elevation of the floodplain is e (0) and the average (or expected) floodplain elevation at time t is e (t). Corresponding to the elevation $e(t)$, a threshold discharge $Q_T(t)$ is defined by:

$$Q_T(t) = \left(\frac{e(t) - e_{min}}{c}\right)^{\frac{1}{f}} \tag{8}$$

where e_{min} is the minimum riverbed elevation. Sediment deposition will occur for a flood with discharge Q at time t only if $Q > Q_T(t)$. Under the assumption that flood arrivals constitute a Poisson process with rate λ floods per year, then the average incremental increase, Δe, per year is approximated by:

$$\Delta e(t) = D_f \lambda_T(t) \Delta t \tag{9}$$

where

$$\lambda_T(t) = \lambda[1 - F(Q_T(t))] \tag{10}$$

Δt is one year, and D_f can be either $\overline{\mathrm{D}}$ or D_L. Because the quantity $\lambda_T(t)$ is equal to the flood rate λ multiplied by an exceedance probability, which is decreasing in time as the floodplain grows, it represents an 'effective' rate of occurrence of floods. The incremental increase each year, Δe, is added to the elevation, $e(t)$, of the

Table III. Estimates of net sediment deposition per flood

River	Median discharge (m^3 s^{-1})	Concentration* for median discharge (mg l^{-1})	Median flood duration (days)	Cross-sectional average deposition (cm)			Levee deposition (cm)		
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
Powder	25·3	5600	5	−3·5	1·5	9·0	−5·5	2·4	26·0
k				0·0018	0·00074	0·0045	−0·0027	0·0012	0·0130
Beatton	277	5300	17	−12	4·8	29	−18	7·8	84
Brandywine	20·7	100	2	−0·03	0·01	0·06	−0·04	0·02	0·19
Little Missouri	39·4	3300	5	−2·1	0·9	5·3	−3	1·4	15

Empirical equation $D_f = k\, V_s\, \overline{\mathrm{C}}\, \Delta T$, with $V_s = 1{\cdot}0$ cm s^{-1} (very fine sand) and assuming a bulk density of 1·20 g cm^{-3}
* Concentrations were calculated using the following empirical equations:
Beatton River: $\overline{\mathrm{C}}$ (mg l^{-1}) = 11 $Q^{1{\cdot}1}$ (m^3 s^{-1}), $r^2 = 0{\cdot}98$; sediment data 24 May 1988 to 13 June 1992 were provided by Environment Canada, Environmental Service and Applications, Vancouver, BC
Brandywine Creek: $\overline{\mathrm{C}}$ (mg l^{-1}) = 1·4 $Q^{1{\cdot}4}$ ($m^3 s^{-1}$), estimated from Wolman (1955, figure 21)
Little Missouri River: $\overline{\mathrm{C}}$ (mg l^{-1}) = 450 $Q^{0{\cdot}54}$ ($m^3 s^{-1}$), r^2=0·31, 80 measurements, US Geological Survey – North Dakota 1978–1994)

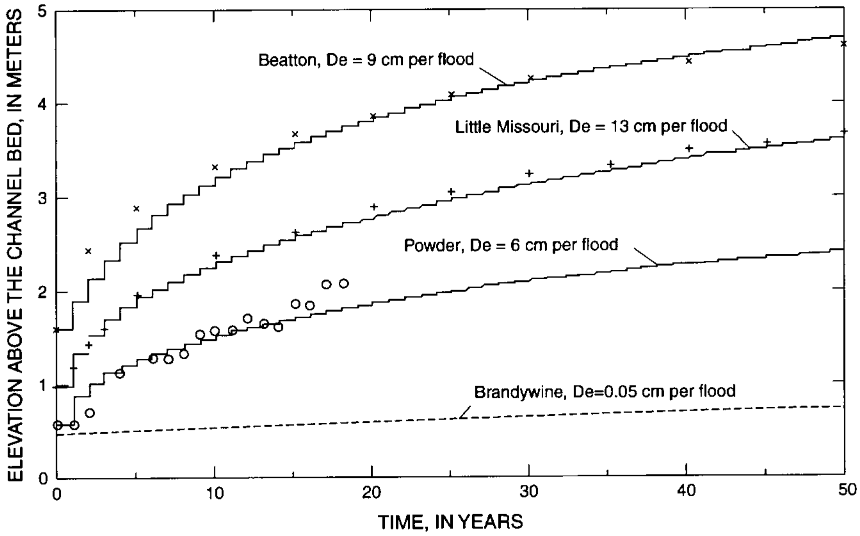

Figure 4. Theoretical floodplain growth curves for four floodplains using a constant net deposition per flood that minimizes the root-mean-square error between the theoretical and empirical growth curves or between the theoretical and field measured growth curves. Time is from the beginning of floodplain growth. The average number of floods per year is listed in Table I. Data for the Beatton River were taken from Nanson and Beach (1977), and for the Little Missouri River from Everitt (1968, figure 5). Data for the Powder River are measured elevations of the floodplain crest at section PR120 described by Moody and Meade (1990). One data point for Brandywine Creek (at about 1450 years and at an elevation of 1·7 m) was published by Wolman and Leopold (1957) but is not shown on this figure.

floodplain and a new threshold discharge is computed for the following year using Equation 8. Repeating this procedure iteratively generates a stair-like theoretical growth curve for the elevation of the floodplain as a function of time.

RESULTS

Theoretical growth curves were calculated for four floodplains using the incremental-growth model and then compared to the floodplain growth curves determined by direct measurements for the Powder River and by indirect measurements for the Beatton River, Brandywine Creek and Little Missouri River (Figure 4). Theoretical growth curves for the Powder River were compared to the annual or biannual measurements of the growth of channel-expansion floodplains at the five sections along Powder River for 18 years after the flood in 1978 (Moody and Meade, 1990; Moody *et al.*, 1999). The theoretical curves for the Beatton and Little Missouri Rivers were compared to the empirical growth curves based on dendrochronology techniques (Nanson and Beach, 1977; Everitt, 1968). The theoretical curve for Brandywine Creek was compared to the single measurement of time and elevation (a carbon-14 date gave an age of 1450 ± 200 years BP and the elevation of the floodplain was 1·7 m; Wolman and Leopold, 1957). Rather than selecting a single value of D_f from Table III, we obtained a least-squares estimate by varying the values of D_f until we minimized the mean-square error between the theoretical growth curve and the empirical (Beatton and Little Missouri) or measured (Powder River) growth curves. For Brandywine Creek, the theoretical growth curve was started at 0·48 m above the channel bed (not at the channel bed as shown in Wolman and Leopold, 1957) corresponding to the water surface at the mean annual discharge. With only one point for the Brandywine, the deposition per flood could not be determined by minimizing the mean-square error, so the net deposition per flood was selected which produced a theoretical growth curve that passed between a horizontal line segment representing the error bars for the uncertainty in the age of the floodplain surface (not shown in Figure 4 but at an elevation of 1·7 m and drawn from 1250 to 1650 years).

The least-squares estimates of the net deposition per flood, *De*, were all within the range of possible estimated values (Table III). Estimates for the five sections along the Powder River were greater than the

mean or median values (Table II) and ranged from 5–6 cm/flood (only PR120 is shown in Figure 4). The model accounted for 73–90 per cent of the total variance about the temporal mean elevation. For the Beatton River, the least-squares estimate was 9 cm/flood and the model accounted for 97 per cent of the total variance and for the Little Missouri River it was 13 cm/flood and the model accounted for 99 per cent of the total variance. For the Brandywine, a net deposition of 0·05 cm/flood produced a theoretical growth curve that passed between the error bars. Most predicted values of the net sediment deposition per flood are only two to three times larger than the mean in Table III with the exception of the Little Missouri River. All predicted values, however, fall within the ranges of net sediment deposition per flood estimated using the empirical method calibrated using Powder River data.

DISCUSSION

The incremental-growth model produces reasonable growth curves for vertically accreting floodplains of the channel-expansion type on Powder River and for unknown types of floodplain along the Beatton River, Brandywine Creek and Little Missouri River. In this section, we will examine several issues associated with this model: (1) flood sedimentation, (2) channel-bed elevation, and (3) general application of the model to other rivers in the world.

Flood sedimentation

Net sediment deposition is a combination of two independent processes: sediment deposition and sediment erosion. The physics of these processes are different and conceptual models (Mertes, 1990; Zwolinski, 1992) assume that two erosional maxima occur (one during the rapid rise in stage and one during the rapid fall in stage) and deposition occurs essentially in phase with the hydrograph. While the frequency distribution of net sediment deposition per flood for the Powder River looks normal, it is still skewed and has both positive and negative values (not indicative of a log-normal distribution) which might result from the difference of two log-normal distributions. In this case, the mean value for only the deposition process would be greater and the variance less than the net sediment deposition values. This may explain why the least-squares estimates were greater than the mean and median values in Table II. Measurements of net sediment deposition are relatively easy to make (measurements before and after flood) but the use of these data complicates interpretations. Net deposition for aggrading floodplains is positive and the incremental-growth model always predicts a monotonically increasing elevation of the floodplain. However, observed net sediment deposition per flood values in Table II are both positive and negative so that the actual floodplain sometimes increases and then decreases during any specific year but on average it increases over the secular time scale. Separate measurements of erosion and deposition during several floods would provide data to define a joint probability model of erosion and deposition. Such an improved model could incorporate both processes to determine the net sediment deposition during floods.

The net sediment deposition for Powder River has a relatively narrow range (about one order of magnitude) and even catastrophic floods vary by only about two orders of magnitude (Bridge and Leeder, 1979). Net sediment deposition per flood for the Powder River did not indicate any definite increase with time even though the threshold discharge did increase as the floodplain grew vertically upward. One might expect that the larger floods required to inundate the higher floodplain would have deposited more sediment. Because they did not, this then might suggest that larger floods, while they deposit more sediment, also erode more sediment such that the relatively narrow range in net sediment deposition is smaller than might otherwise be expected. The relatively narrow range of net sediment deposition might also be attributed to the fact that only the top portion of water and sediment in a channel above the mean elevation of the floodplain enters the floodplain (Parker *et al.*, 1996). The vertical gradient of the suspended-sediment distribution in this top portion is less than the gradient near the bottom so that the concentration is relatively uniform and may only vary a few orders of magnitude within the narrow range of flood discharges.

The empirical constant, k (in Equation 5), is estimated from the Powder River data and this introduces the question of whether that constant is appropriate for other rivers. It is essentially a measure of the efficiency of the net deposition process independent of the sediment concentration but dependent upon the turbulent or

unsteady flow conditions. By similarity these flow conditions are the same over any floodplain if the Reynolds number and other dimensionless numbers are the same. The use of the empirical constant has, therefore, some general application. The range of values of k in Table III probably reflects a range in Reynolds number for the Powder River as well as the other floodplains. The least-squares estimate of the net sediment deposition for the Little Missouri River (13 cm/flood) was about 10 times greater than the mean or median estimate in Table III and may reflect more variability in flow conditions.

The deposition process has been initially conceived as a advective process transporting suspended sediment from the channel across the floodplain. Several observers (Kesel *et al.*, 1974; Pizzuto, 1987) have reported that sediment thickness decreases exponentially away from the channel and Parker *et al.* (1996) have shown theoretically that the concentration varies exponentially with distance as water flows over a point bar. Sediment deposition on the floodplain probably initially reflects this exponential concentration but it is very likely that during some stages of a flood, the bedload transport process advects some sediment from the levee to distal portions of the floodplain and perhaps after the flood has receded the aeolian transport process diffuses additional sediment away from the crest or levee.

A wide range of sediment deposition rates has been published for Brandywine Creek. Both the empirical (0·01 cm/flood) and the predicted (0·05 cm/flood) estimates of the net sediment deposition per flood for Brandywine Creek were less than the value of 1·4 cm/flood estimated by Pizzuto (1987) for the post-settlement period (*c.* 1730 to 1980s). During the pre-settlement period, an average overbank accretion rate of 0·05 cm/year was calculated by Ritter *et al.* (1973) from seven estimates spanning 1200 to 6200 years BP. Erosion peaked during the agricultural period (1850 to 1930) and was reduced about 200 per cent (Jacobson and Coleman, 1986) during the recent period (1930 to 1980s). The empirical estimate of the net sediment deposition per flood was based only on data for the recent period and so reflects a soil erosion rate higher than the pre-settlement period but probably less than the agricultural period included in Pizzuto's (1987) estimate. The net sediment deposition, 0·05 cm/flood, predicted by the incremental-growth model seems reasonable because it represents an average value for at least the last 1450 years and includes high values during the post-settlement period but also includes low values inferred for the much longer pre-settlement period. If Wolman and Leopold's hypothetical curve is examined closely, the apparent depositional 'rate' per flood for Brandywine Creek seems large. If Figure 64 (Wolman and Leopold, 1957) is enlarged and the elevation of the floodplain is scaled off the enlarged figure, about 91 cm of accretion has occurred in 10 years. Dividing by the thickness (0·15 cm) they assumed to be deposited per flood gives about 606 floods or about 61 floods per year. This is much too large for the number of floods per year, so that it should probably be interpreted as 'the average number of days per year on which a given stage is equalled or exceeded', not the number of floods. This is equivalent to a deposition of about 9 cm/year or 0·5 cm per flood event (assuming 17·8 flood events per year) and is probably also reasonable for the recent or earlier agricultural period but is probably too high if the pre-settlement period is considered. Thus, the difference in the assumed deposition rate (9 cm/year) used by Wolman and Leopold (1957) and the net deposition predicted by the incremental-growth model (0·05 cm/flood) illustrates the importance in knowing the historical land use before predicting the growth of flood plains by vertical accretion.

Bed elevation

We established that the channel-bed elevation of Powder River has not shown a significant trend with time since the 1978 flood. But we do not have this information for the Beatton River which had the most rapid growth of all four floodplains (Figure 4). However, vertical aggradation and degradation of both the channel bed and floodplain are possible. Because channel aggradation might be an explanation for the rapid growth rate of the Beatton River floodplain, the effect of channel-bed aggradation was investigated for the Beatton River. The channel bed must increase at a slower rate than the floodplain because the empirical floodplain growth curves always indicated that the floodplain is increasing relative to the channel bed. Therefore, the incremental-growth model was run for the Beatton River assuming three different growth rates for the channel bed: $0{\cdot}50D_f$, $0{\cdot}25D_f$ and $0{\cdot}10D_f$. The net sediment deposition was again determined by minimizing the mean-square error. The corresponding estimated values of D_f were 5, 7 and 8 cm/flood, and the model accounted for 66, 86 and 94 per cent of the total variance, respectively. Increasing the elevation of the channel

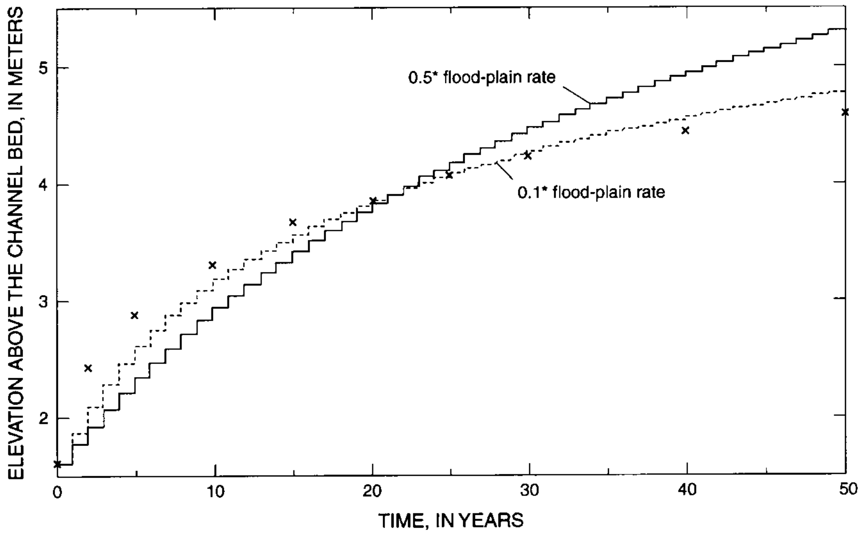

Figure 5. Sensitivity of the incremental-growth model to channel aggradation using the Beatton River. Time in years is from the beginning of floodplain growth. × = Data from (Nanson and Beach, 1977), figure 24

bed decreases the average water depth and corresponding threshold discharge, thus increasing the flood probability and the number of floods. At first, the floodplain grows slowly because the optimal (determined by minimal mean-square error for the entire growth curve) net sediment deposition per flood is smaller, but it eventually grows more rapidly than when the channel bed remains fixed (Figure 5). However, for the floodplain along the Beatton River, the theoretical growth curve which best represents the floodplain is the one when no channel bed aggradation occurs.

Application to other floodplains

The incremental-growth model predicts the overbank vertical accretion with time for a floodplain and is applicable for those rivers or reaches of a river where point-bar lateral migration or channel aggradation are not dominant processes. This excludes rivers with avulsions which are common when the channel bed is aggrading relative to the floodplain (Howard, 1992). The model was developed for floodplains where the width of the floodplain was less than the width of the channel, so that caution must be used if the model is applied to wider floodplains. Rivers should also have a small ratio of bedload to suspended load. This will, in general, be the larger rivers of the world (Meade *et al.*, 1990) for which Richards (1982) indicates that bedload transport represents about 1–10 per cent of the total load transport. Few rivers have measurements of both bedload and suspended load transport and for some rivers the bedload has been calculated using the size distribution of the bed material, velocity measurements and bedload equations (Colby and Hembree, 1955; Graf, 1971).

Ratio of bedload to suspended load for the Mississippi River varies along the length of the river. In the impounded reach of the Upper Mississippi River above St Louis, Missouri, the ratio is, not surprisingly, relatively low ($\sim$5 per cent; Table IV) because this reach is controlled by 26 locks and dams forming navigation pools, thus the incremental-growth model should work well to predict the slow rise of a floodplain by future filling of backwater areas which is a concern of communities along the river. The Upper Mississippi River below St Louis has been channelized which may be the cause of the large ratio ($\sim$26 per cent) of bedload to suspended load. Vertical deposition is unlikely to be an important process in this reach of the river and the channelization may retard the growth of any floodplains. Below the confluence with the Ohio River, the Lower Mississippi River is engineered but still exhibits a meandering character; the ratio of bedload to suspended load decreases but seems a little high for the successful use of the model throughout the entire

Table IV. Ratio of bedload to suspended load for selected rivers

River	Annual-mean discharge (10^9 m^3 /year)	Number of measure ments	Mean ratio of bedload to suspended load (%)	Method	Reference and comments
Fraser at Agassiz and Mission, British Columbia	284	17	1·0	Measured	Church *et al.* 1987; average of annual totals
Tanana at Fairbanks, Alaska	18	54	1·9 ± 1·7	Measured	Burrows and Harrold, 1983; Burrows *et al.*, 1981; Williams and Rosgen, 1989; US Geological Survey--Alaska, 1993
Susitna near Talkeetna, Alaska	45	39	2·4 ± 1·8	Measured	Knott and Lipscomb, 1985 Williams and Rosgen, 1989 US Geological Survey--Alaska, 1993
Upper Amazon, Brazil	1500	7	8·6 ± 3·1	Calculated	Posada, 1995; Carvalho and da Cunha, 1998
Middle Solimões, Brazil	3200	6	6·4 ± 1·9	Calculated	Posada, 1995; Dunne *et al.*, 1998
Lower Solimões, Brazil	3200	4	7·3 ± 3·8	Calculated	Posada, 1995; Dunne *et al.*, 1998
Amazon, Brazil	6300	6	4·3 ± 2·2	Calculated	Posada, 1995; Meade, 1996
Impounded Mississippi	93	3	4·8 ± 1·1	Calculated	Posada, 1995; Moody and Meade, 1992
Mississippi at St. Louis	165	na	5	Calculated	Jordan, 1965; Moody and Meade, 1992
Upper Mississippi	165	9	26· ± 12	Calculated	Posada, 1995; Moody and Meade, 1992
Lower Mississippi	487	23	16· ± 7·5	Calculated	Posada, 1995; Moody and Meade, 1992
Clearwater at Spalding, Idaho	14	47	9·5 ± 17·3	Measured	Emmett and Seitz, 1973; Williams and Rosgen, 1989; US Geological Survey--Idaho, 1992
Apure River, Venezula	80	14	10· ± 8·1	Calculated	Posada, 1995; Meade, 1994 (fig. 3)
Orinoco, Venezuela	1200	28	19· ± 19	Calculated	Posada, 1995, Meade, 1996
Snake near Anatone, Washington	20	35	13·6 ± 18·5	Measured	Emmett and Seitz, 1973; Williams and Rosgen, 1989; US Geological Survey--Washington, 1992
Pilcomayo near Talula; Bolivia	∼0·63	36	15· ± 15	Measured	Vollmers and Espada, 1983; measurements only in the wet season Jan.–Apr.
Brahmaputra and Ganges	970	na	>20·	Inferred	Coleman, 1969; Meade, 1996
Congo (Zaire) near Boma,	1450	na	77·	Measured	Peters, 1978
Lewis, Baffin Island, Canada	0·17	3	79·1 ± 2·3	Measured	Church, 1972; 2 month runoff
Wisconsin at Muscoda, Wisconsin	7·7	20	173 ± 170	Measured	Williams and Rosgen, 1989; US Geological Survey--Wisconsin, 1992
East Fork near Pinedale, Wyoming	0·095	31	510 ± 560	Measured	Williams and Rosgen, 1989

Value after ± symbol is the standard deviation; na = not available.

reach, but it may be applicable in certain small reaches of the river. This is the reach of the Mississippi River where the point-bar lateral migration type of floodplain exists even though engineered revetments in recent time have reduced lateral migration.

Ratio of bedload to suspended load for the Solimões–Amazon River decreases along the length of the river. Several reaches of the Solimões–Amazon River have been defined by lithologic zones and structure features (Mertes *et al.*, 1996) and have different floodplains of the medium-to low-energy type (Class B and Class C; Nanson and Croke, 1992). A relatively steep upstream reach between Iquitos, Peru, and the mouth of the Içа River has a ratio of bedload to suspended load of about 9 per cent (Table IV); a reach with rapid channel migration extending almost to the mouth of the Purús River has a ratio of about 6 per cent; a transitional reach from the Purús River to the mouth of the Madeira River has a ratio of about 7 per cent; an overbank depositional reach extending downstream to Óbidos has a ratio of about 4 per cent; and the deltaic reach has no measurements. The incremental model should be applicable in the overbank depositional reach with the lowest bedload to suspended load ratio. It will probably also work in certain areas of the upstream reaches where spatial variability will produce local areas with a lower ratio of bedload to suspended load and thus creates a mosaic of vertically accreting and lateral migration type floodplains that may help explain some of the biotic diversity observed by Salo *et al.* (1988).

The ratio of bedload to suspended load for the Orinoco River is greater and more variable than either the Mississippi or Solimões–Amazon Rivers. The Orinoco River is forced against the resistant Guayana Shield

by its Andean tributaries, and the mean ratio for 11 sites along the Orinoco is about 19 per cent (Table IV). The large variability (standard deviation of about 19 per cent) is probably a result of measurements being made in both the wet and the contrasting dry season (Meade, 1994). The Apure River, an Andean tributary flowing across the Ilanos, has a somewhat lower ratio (Table IV) suggesting that the incremental-growth model might best be used for some tributaries of the Orinoco rather than the Orinoco itself.

While the Brahmaputra River is large, no bedload measurements have been reported to date. Coleman (1969) did make measurements of bedform transport (dunes and sand waves: 60–200 m/day), and these measurements are about 50 times greater than the bedform transport ($\sim$ 2 m/day) reported by Mertes (1985) for the Amazon River so it seems likely that for the Brahmaputra River, the ratio of bedload to suspended load is not negligible and the incremental-growth model would not be applicable.

SUMMARY

The incremental-growth model is a one-dimensional model for predicting the vertical accretion of the levee or the cross-sectional average elevation of floodplains. It was developed from field data for channel-expansion, vertically accreting floodplains along the Powder River where: (1) the bedload transport is 2–7 per cent of the suspended load transport; (2) the channel bed shows no significant changes in elevation with time; and (3) the width of the floodplain is less than the width of the channel. The model is essentially an unsteady model focusing on incremental deposition during individual floods and having a secular time scale of several decades to a hundred years. It differs from the steady-state, two-dimensional models used to predict the development of basin-scale sandstone over long time scales or point-bar development over shorter time scales, and from very short time scale models used to predict spatial distribution over complex topographic floodplains during single floods. The incremental-growth model requires: (1) a partial-duration flood frequency probability distribution; (2) the average number of floods per year; (3) a stage–discharge relation; and (4) estimates of the net sediment deposition per flood based on an empirically derived constant and some suspended sediment and discharge measurements. It has been used to predict the growth of floodplains along three other rivers with quite different hydraulic and sedimentologic characteristics than the Powder River and is applicable to some large rivers throughout the world or to those reaches of rivers which have vertically aggrading floodplains interspersed among other type of floodplains.

ACKNOWLEDGEMENTS

John Pitlick, University of Colorado, reviewed a paper concerning the growth of some flood plains along the Powder River and made a suggestion which led to this re-examination of other works on flood-plain growth. Bob Meade, Jim Pizzuto and Gordon Wolman made review comments that improved the content of each version of the paper. John Bridge and Ian Foster made comments on a later version that led to some extensive rethinking of the paper. Lynne Campo, Environment Canada, and Mike Church, University of British Columbia, were both helpful in providing data for the Beatton River. Bob Meade and Leal Mertes provided insights into the workings of some of the larger rivers of the world.

REFERENCES

Allen, J. R. L. 1970. 'A quantitative model of grain size and sedimentary structures in lateral deposits', *Geological Journal*, **7**, 129–146.

Allen, J. R. L. 1977. 'Changeable rivers: Some aspects of their mechanics and sedimentation', in Gregory, K. J. (Ed.), River Channel Changes, John Wiley & Sons, New York, 16–45.

Barnes, H. H. Jr. 1967. Roughness characteristics of natural channels US Geological Survey Water-Supply Paper **1849**, pp. 213.

Bayley, P. B. 1995. 'Understanding large river-floodplain ecosystems', *BioScience*, **45**, 153–158.

Blake, D. H. and Ollier, C. D. 1971. 'Alluvial plains of the Fly River, Papua', *Zeitschrift für Geomorphologie, N.F., Suppl. Bd.* **12**, 1–17.

Brakenridge, G. R. 1988, 'River flood regime and floodplain stratigraphy', in Baker, V. R., Kochel, R. C. and Patton, P. C. (Eds), Flood Geomorphology, John Wiley & Sons, New York, 139–156.

Bridge, J. S. 1975. 'Computer simulation of sedimentation in meandering streams', *Sedimentology*, **22**, 3–43.

Bridge, J. S. and Leeder, M. R. 1979. 'A simulation model of alluvial stratigraphy', *Sedimentology*, **26**, 617–644.

Bridge, J. S. and Mackey, S. D. 1993. A revised alluvial stratigraphy model International Association of Sedimentologists, Special Publications **17**, 319–336.

Brierley, G. J., Ferguson, R. J. and Woolfe, K. J. 1997. 'What is a fluvial levee?', *Sedimentary Geology*, **114**, 1–9.

Brooks, C. E. P. and Carruthers, N. 1953. Handbook of Statistical Methods in Meteorology, Her Majesty's Stationery Office, London.

Burkham, D. E. 1972 Channel changes of the Gila River in Safford Valley, Arizona 1846–1970, US Geological Survey Professional Paper **655-G**, pp. 24.

Burrows, R. L. and Harrold, P. E. 1983. Sediment transport in the Tanana River near Fairbanks, Alaska, US Geological Survey Water-Resources Investigations Report **83-4064**, pp. 116.

Burrows, R. L., Emmett, W. W. and Parks, B. 1981. Sediment transport in the Tanana River near Fairbanks, Alaska, 1977–79, US Geological Survey Water-Resources Investigations Report **81-20**, pp. 56.

Carvalho, N. O. and da Cunha, S. B. 1998. Estimative da carga sólida do Rio Amazonas e seus principais tributários para a foz e oceano: uma retrospectiva, A Água em Revista, Serviço Geológico do Brasil, CPRM, 6: 10, 44–58.

Cazanacli, D. and Smith, N. D. 1997. 'The evolution of natural levees in the Saskatchewan River, Cumberland Marshes, Saskatchewan', GSA Abstracts with Program, A-112.

Chow, V. T. 1954. 'The log-probability law and its engineering application', *Proceedings of the American Society of Civil Engineers* **80**, 1–25.

Chow, V. T. 1959. Open-Channel Hydraulics, McGraw Hill, New York, pp. 680.

Chow, V. T. 1964. 'Statistical and probability analysis of hydrologic data', Part I, in Chow, V. T. (Ed.), Handbook of Applied Hydrology, Section 8-I, McGraw-Hill, New York, 8–20.

Chow, V. T. Maidment, D. R. and Mays, L. W. 1988. Applied Hydrology, McGraw-Hill, New York, pp. 374.

Church, M. 1972. Baffin Island Sandurs: A study of Arctic fluvial process, Geological Survey of Canada Bulletin **216**, pp. 208.

Church, M. McLean, D. G. Kostaschuk, R. and Tassone, B. 1987. 'Sediment transport in lower Fraser River: Summary of results and field excursion guide', International Association of Hydrological Sciences, IUGG, XIX General Assembly, Vancouver, Canada, 9–22 August 1987, 90.

Colby, B. R. and Hembree, C. H. 1955. Computations of total sediment discharge, Niobrara River near Cody, Nebraska, US Geological Survey Water-Supply Paper **1357**, pp. 187.

Coleman, J. M. 1969. 'Brahmaputra River: Channel processes and sedimentation', *Sedimentary Geology*, **3**, 129–239.

Collins, D. L. and Flynn, K. M. 1978. A summary of measured hydraulic data for the series of steady and unsteady flow experiments over uniform grass roughness, US Geological Survey Open-File Report **78-808**, pp. 826.

Conover, W. J. 1980. Pratical Nonparametric Statistics, 2nd edition, John Wiley & Sons, New York, pp. 493.

Duckstein, L. Fogel, M. M. and Kisiel, C. C. 1972. 'A stochastic model of runoff-producing rainfall for summer type storms', *Water Resources Research*, **8**, 410–421.

Dunne, T. Mertes, L. A. K. Meade, R. H. Richey, J. E. and Forsberg, B. R. 1998. 'Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil', *Geological Society of America Bulletin*, **110**, 450–467.

Emmett, W. W. and Seitz, H. R. 1973. Suspended and bedload sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho, March 1972 through June 1973, US Geological Survey Basic-Data Report, pp. 78.

Engelund, F. 1970. 'Instability of erodible beds', *Journal of Fluid Mechanics*. **42**, 225–244.

Everitt, B. L. 1968. 'Use of the cottonwood in an investigation of the recent history of a flood plain', *American Journal of Science*, **266**, 417–439.

Friedman, J. M. Osterkamp, W. R. and Lewis, W. M. Jr. 1996. 'The role of vegetation and bed-level fluctuations in the process of channel narrowing', *Geomorphology*, **14**, 341–351.

Gilbert, G. K. 1917. Hydraulic-mining débris in the Sierra Nevada, US Geological Survey Professional Paper **105**, pp. 154.

Graf, W. H. 1971. Hydraulics of Sediment Transport, McGraw-Hill, New York, pp. 513.

Graf, W. L. 1994. Plutonium in the Rio Grande: Environmental change and contamination in the nuclear age, Oxford University Press, New York, pp. 329.

Hembree, C. H. Colby, B. R. Swenson, H. A. and Davis, J. R. 1952. Sedimentation and chemical quality of water in the Powder River drainage basin Wyoming and Montana, US Geological Survey Circular **170**, pp. 92.

Hickin, E. J. and Nanson, G. C. 1975. 'The character of channel migration on the Beatton River, northeastern British Columbia, Canada', *Geological Society of America Bulletin*, **86**, 487–494.

Howard, A. D. 1992. 'Modeling channel migration and floodplain sedimentation in meandering streams', in Carling, P. A. and Petts, G. E. (Eds), Lowland Floodplain Rivers: Geomorphological Perspectives, John Wiley & Sons, New York, 1–41.

Hupp, C. R. and Osterkamp, W. R. 1985. 'Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms', *Ecology*, **66**(3), 670–681.

Jackson, R. G. II. 1976. 'Depositional model of point bars in the lower Wabash River', *Journal of Sedimentary Petrology*, **46**(3), 579–594.

Jacobson, R. B. and Coleman, D. J. 1986. 'Stratigraphy and recent evolution of Maryland Piedmont flood plains', *American Journal of Science*, **286**, 617–637.

James, C. S. 1985. 'Sediment transfer to overbank sections', *Journal of Hydraulic Research*, **23**, 435–452.

Johnson, N. L. and Kotz, S. 1970. Continuous Univariate Distributions, John Wiley & Sons, New York, 80–87.

Jordan, P. R. 1965. Fluvial sediment of the Mississippi River at St. Louis, Missouri, US Geological Survey Water-Supply Paper **1802**, pp. 89.

Kennedy, V. C. 1956. Geochemical studies in the southwestern Wisconsin zinc-lead area, US Geological Survey Bulletin **1000-E**, pp. 220.

Kesel, R. H. Dunne, K. C. McDonald, R. C. and Allison, K. R. 1974. 'Lateral erosion and overbank deposition of the Mississippi River in Louisiana caused by 1973 flooding', *Geology*, 461–464.

Knight, D. W. and Demetriou, J. D. 1983. 'Flood plain and main channel flow interaction', *Journal of Hydraulic Engineering, ASCE*, **109**, 1073–1092.

Knight, D. W. and Hamed, M. E. 1984. 'Boundary shear in symmetrical compound channels', *Journal of Hydraulic Engineering*, **110**,

1412–1430.
Knott, J. M. and Lipscomb, S. W. 1985. Sediment discharge data for selected sites in the Susitna River basin, Alaska, October 1982 to February 1984, US Geological Survey Open-File Report **85-157**, pp. 68.
Lambert, C. P. and Walling, D. E. 1987. 'Floodplain sedimentation: A preliminary investigation of contemporary deposition within the lower reaches of the River Culm, Devon, UK', *Geografiska Annaler*, **69**, 393–404.
Leenaers, H. and Schouten, C. J. 1989. 'Soil erosion and floodplain soil pollution: Related problems in the context of a river basin', in Hadley, R. F. and Ongley, E. D. (Eds.), Sediment and the Environment, International Association of Hydrological Sciences Publication **184**, 75–83.
Leopold, L. B. Wolman, M. G. and Miller, J. P. 1964. Fluvial Processes in Geomorphology, W. H. Freeman and Company, San Francisco, pp. 522.
Lewin, J. Davise, B. E. and Wolfenden, P. J. 1977. 'Interactions between channel change and historic mining sediments', in Gregory, K. J. (Ed.), River Channel Changes, John Wiley & Sons, New York, 353–368.
Litke, D. W. 1983. Suspended sediment in selected streams of southeastern Montana, US Geological Survey Water-Resources Investigations 82-4087 pp. 52.
Marron, D. C. 1992. 'Floodplain storage of mine tailings in the Bell Fourche River system: A sediment budget approach', *Earth Surface Processes and Landforms*, **17**, 675–685.
Meade, R. H. 1994. 'Suspended sediments of the modern Amazon and Orinoco Rivers', *Quaternary International*, **21**, 29–39.
Meade, R. H. 1996. 'River sediment inputs to major deltas', in Milliman, J. D. and Haq, B. U. (Eds), Sea-Level Rise and Coastal Subsidence Causes, Consequences, and Strategies, Kluver Academic, Dordrecht, 63–85.
Meade, R. H. Yuzyk, T. R. and Day, T. J. 1990. 'Movement and storage of sediment in rivers of the United States and Canada', in The Geology of North American, Vol. O-1, Surface Water Hydrology, Geological Society of America, 255–280.
Melton, F. A. 1936. 'An empirical classification of flood-plain streams', *Geographical Review*, **26**, 593–609.
Mertes, L. A. K. 1985. Floodplain development and sediment transport in the Solimões-Amazon River in Brazil, Master's thesis, University of Washington, pp. 108.
Mertes, L. A. K. 1990. Hydrology, hydraulics, sediment transport and geomorphology of the central Amazon floodplain, Ph D thesis, University of Washington, pp. 225.
Mertes, L. A. K. Dunne, T. and Martinelli, L. A. 1996. 'Channel-floodplain geomorphology along the Solimões-Amazon River, Brazil', *Geological Society of America Bulletin*, **108**, 1089–1107.
Miller, J. R. and Wells, S. G. 1986. 'Types and processes of short-term sediment and uranium-tailings storage in arroyos: an example from the Rio Puerco of the West, New Mexico', in Hadley, R.F. (Ed.), Drainage Basin Sediment Delivery, IAHS Publication, **159**, 335–353.
Moody, J. A. and Meade, R. H. 1990. Channel changes at cross sections of the Powder River between Moorhead and Broadus, Montana, 1975-88, US Geological Survey Open-File Report 89-407, pp. 252.
Moody, J. A. and Meade, R. H. 1992. Hydrologic and sedimentologic data collected during three cruises at low water on the Mississippi River and some of it tributaries, July 1987–June 1988, US Geological Survey Open-File Report 91-485, pp. 143.
Moody, J. A. Pizzuto, J. E. and Meade, R. H. 1999. 'Ontogeny of a flood plain', *Geological Society of America Bulletin*, **111**, 291–303.
Nanson, G. C. 1980. 'Point bar and floodplain formation of the meandering Beatton River, northeastern British Columbia, Canada', *Sedimentology*, **27**, 3–29.
Nanson, G. C. 1986. 'Episodes of vertical accretion and catastrophic stripping: A model of disequilibrium flood-plain development', *Geological Society of America Bulletin*, **97**, 1467–1475.
Nanson, G. C. and Beach, H. F. 1977. 'Forest succession and sedimentation on a meandering-river floodplain, northeast British Columbia, Canada', *Journal of Biogeography*, **4**, 229–251.
Nanson, G. C. and Croke, J. C. 1992. 'A genetic classification of floodplains', *Geomorphology*, **4**, 459–486.
Nanson, G. C. and Young, R. W. 1981. 'Overbank deposition and floodplain formation on small coastal streams of New South Wales', *Zeksehrift Geomorphologie N. F.*, **25**, 332–347.
National Research Council 1992. Committee on Restoration of Aquatic Ecosystems, Science, Technology and Public Policy, National Academy Press, Washington, D.C., pp. 552.
Nicholas, A. P. and Walling, D. E. 1997a. 'Modelling flood hydraulic and overbank deposition on river floodplains', *Earth Surface Processes and Landforms*, **19**, 59–77.
Nicholas, A. P. and Walling, D. E. 1997b. 'Investigating spatial patterns of medium-term overbank sedimentation on floodplains: a combined numerical modelling and radiocaesium-based approach', *Geomorphology*, **19**, 133–150.
Osterkamp, W. R. and Hedman, E. R. 1982. Perennial-streamflow characteristics related to channel geometry and sediment in Missouri River basin, US Geological Survey Professional Paper **1242**, pp. 20.
Parker, G. 1978. 'Self-formed straight rivers with equilibrium banks and mobile bed, Part 1, The sand-silt river', *Journal of Fluid Mechanics*, **89**, 109–125.
Parker, G. Cui, Y. Imran, J. and Dietrich, W. E. 1996. 'Flooding in the lower Ok Tedi, Papua, New Guinea due to the disposal of mine tailing and its ameleoration', in International Seminar on Recent Trend of Floods and their Preventive Measures, 20–21 June 1996, Sapporo, Japan.
Peters, J. J. 1978. 'Discharge and sand transport in the braided zone of the Zaire estuary', *Netherlands Journal of Sea Research*, **12**(3/4) 273–292.
Petts, G. E. Large, A. R. G. Greenwood, M. T. and Bickerton, M. A. 1992. Floodplain assessment for restoration and conservation: Linking hydrogeomorphology and ecology', in Carling, P. A. and Petts, G. E. (Eds), Lowland Floodplain Rivers: Geomorphological Perspectives, John Wiley & Sons, New York, 217–234.
Pizzuto, J. E. 1987. 'Sediment diffusion during overbank flows', *Sedimentology*, **34**, 301–317.
Posada, L. G. 1995. Transport of sand in deep rivers, PhD Thesis, Colorado State University pp. 158.
Richards, K. 1982. Rivers: Form and Process in Alluvial Channels, Methuen, New York, pp. 358.
Ritter, D. F. Kinsey, W. F. III. and Kauffman, M. E. 1973. 'Overbank sedimentation in the Delaware River Valley during the last 6000 years', *Science*, **179**, 374–375.

Rouvé, G. and Stein, C. J. 1990. 'Compound channel flow computation –theory and practice', EOS, American Geophysical Union, Abstracts, April 24, 1990, pp. 509.
Salo, J. 1990. 'External processes influencing origin and maintenance of inland water-land ecotones', in Naiman, R. J. and Décamps (Eds.), The Ecology and Management of Aquatic-Terrestrial Ecotones, Parthenon, Carnforth, 37–64.
Salo, J. Kalliola, R. Hakkinen, I. Makinen, Y. Niemela, P. Puhakka, M. and Coley, P. D. 1988. 'River dynaics and the diversity of Amazon lowland forest', *Nature*, **322**, 254–258.
Schumm, S. A. and Lichty, R. W. 1963. Channel widening and flood-plain construction along Cimarron River in southwestern Kansas, US Geological Survey Professional Paper **352-D**, pp. 88.
Sciacca, J. E. 1998. 'Hydrostratigraphic analysis of a complex fluvial deposition system, Sacra-mento County, California', *AAPG Bulletin*, **82**(5A), 858.
Sellin, R. H. J. 1964. 'A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plain', *Lattouille Blanche*, **7**, 793–801.
Stallard, R. F. 1998, 'Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial', *Global Biogeochemical Cycles*, **12**, 231–257.
Stene, L. P. 1980. 'Observations on lateral and overbank deposition–Evidence from Holocene terraces, southwestern Alberta', *Geology*, **8**, 314–317.
Swanson, F. J. 1997. 'Development in river and watershed management from ecosystem perspectives' in 50th Anniversary Meeting of the Japan Society for Erosion Control Engineering, 1997 October 8–9, Tokyo, Japan, 173–181.
Topping, D. J. 1997. Physics of flow, sediment transport, hydraulic geometry, and channel geomorphic adjustment during flash floods in an ephemeral river, the Paria River, Utah and Arizona, PhD thesis, Department of Geological Sciences, University of Washington, pp. 405.
US Department of Agriculture 1978. Strategies for Protection and Management of Floodplain Wetland and other Riparian Ecosystems, Proceedings of the Symposium, 11–13 December 1978, Callaway Gardens, Georgia, pp. 410.
US Geological Survey –Alaska. 1993. Water-resources data for Alaska, water year 1993, US Geological Survey Water-Data Reports **AK-92-1**, pp. 373.
US Geological Survey –Idaho. 1992. Water-resources data for Idaho, water year 1992, US Geological Survey Water-Data Reports **ID-92-2**, pp. 431.
US Geological Survey – North Dakota 1978–1994. Water-resources data for North Dakota, water years 1978–1994, US Geological Survey Water-Data Reports **ND-78-1** to **ND-94-1** (published annually).
US Geological Survey – Washington. 1992. Water-resources data for Washington, water year 1992, US Geological Survey Water-Data Report **WI-92-1**, pp. 459.
US Geological Survey –Wisconsin. 1992. Water-resources data for Wisconsin, water year 1992 US Geological Survey Water-Data Report **WI-92-1**, pp. 545.
Vollmers, H. J. and Espada, G. P. 1983. 'Sediment measurements in the Pilcomayo River in Bolivia', in Proceedings of the Second International Symposium on River Sedimentation, Nanjing, China, Water Resource and Electric Power Press, 1050–1070.
Williams, G. P. and Rosgen, D. L. 1989. Measured total sediment loads (suspended loads and bedloads) for 93 United States streams, US Geological Survey Open-File Report **89–67**, pp. 128.
Wolff, C. G. and Burges, S. J. 1994. 'An analysis of the influence of river channel properties on flood frequency', *Journal of Hydrology*, **153**, 317–337.
Wolman, M. G. 1955. The Natural Channel of Brandywine Creek Pennsylvania, US Geological Survey Professional Paper **271**, pp. 56.
Wolman, M. G. and Leopold, L. B. 1957. River flood plains: Some observations on their formation, US Geological Survey Professional Paper **282-C**, pp. 109.
Wolman, M. G. and Miller, J. P. 1960. 'Magnitude and frequency of forces in geomorphic processes', *Journal of Geology*, **68**, 54–74.
Zwolinski, Z. 1992. 'Sedimentology and geomorphology of overbank flows on meadering river floodplains', *Geomorphology*, **4**, 367–379.